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ABSTRACT

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LEARNERS' MENTAL MODELS OF METALLIC BONDING: A CROSS-AGE STUDY

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Abstract

Mental models of metallic bonding held by learners' from three academic levels, secondary school (year-12), undergraduate and postgraduate, were probed using semi-structured interviews including the use of Interview about Events focus cards depicting metallic properties and cards containing depictions of models from curriculum material. Learners hold realist views about the bonding and structure for metallic substances and prefer the sea of electrons model. However, undergraduate and postgraduate learners commonly utilized concepts from other models, such as the molecular orbital theory, to supplement their descriptions of their mental models. In addition, they were more critical of depicted models and held views of the continuous nature of metallic lattices that were more in accord with the scientific view. Few learners were able to describe the bonding in alloys, and although learners across all three academic levels offered reasonable explanations for the conductivity of metals, they were unable to explain malleability. It is recommended that it may be prudent to postpone the teaching of highly abstract mental models until later in an undergraduate degree program, since exposure to complex and abstract models is more appropriate for learners who wish to continue their studies in chemistry.

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LEARNERS MENTAL MODELS OF METALLIC BONDING: A CROSS-AGE STUDY

INTRODUCTION

The Nature of Mental Models

Scientists and learners construct mental representations in order to interpret their experiences and to make sense of the physical world. Mental models are considered by many authors to be functional evolving systems; that is, many mental models are incomplete and do not have clearly defined boundaries (Hafner & Stewart, 1995). Hence, mental models are often unscientific and quite unstable. As Norman (1983) points out, "people's mental models are frequently deficient in a number of ways perhaps including contradictory, erroneous and unnecessary concepts" (p. 14). Mental models are causal and are functionally defined in the sense that they allow an individual to engage in description, explanation and prediction (Gilbert, & Rutherford, 1998a, 1998b; Hafner & Stewart, 1995). Such models also may be defined in a structural sense and consist of objects, states that objects exist in, and process that are responsible for the objects changing states. However, mental models are unique to the observer: Norman and others (e.g., Glynn & Duit, 1995; Harrison & Treagust, 1996) warn that uncovering an individual's mental model is not easily accomplished. Although mental models represent personal constructs, this does not mean that they are used solely for purely subjective purposes and there is consensus that like other constructs they are subject to social influence (Hesse, 1966). Mental models may serve a number of purposes and function to provide explanations and justifications and to serve as mnemonic devices for memory

enhancement. An important, often overlooked, function that mental models serve is to predict behavior, particularly of physical systems (Williams, Hollan, & Stevens, 1983).

Typologies of Mental Models

Mental models have been classified using a number of typologies. Norman (1983) classified mental models in four ways, the target system—the system that the learner is attempting to study, the conceptual model of that system—an appropriate representation of the target system, the user's mental model of that system, and scientists' conceptualization of the target situation. Mental models also can be divided into physical and conceptual mental models, where "physical models represent the physical world; conceptual models represent more abstract matters" (Johnson-Laird, 1983, p. 422). Hence, physical mental models are mental constructs of physical entities—real or imagined, whereas conceptual mental models are mental constructs of concepts, models or abstractions. However, humans model reality by manipulating internal symbols, that is, mental models function because the components of the mental model have the same relation-structure as that of the object or process being modeled (Anderson, Howe, Tolmie, 1996; Johnson-Laird, 1983). The view of mental models held by Johnson-Laird (1983) is more general than that of Norman (1983)—the latter tending to focus on examples specific to the physical sciences (see also, Rogers & Rutherford, 1992). Interestingly, despite the difference in approach between Johnson-Laird and Norman, they share a number of similarities. For example, both view mental models as incomplete and believe that individuals' ability to operate their models is limited (see also, Anderson et al., 1996; Barsalou, 1992; Glynn & Duit, 1995). The major point of difference between

the two views lies in the stability of mental models. Johnson-Laird suggests that mental models are transitory, whereas Norman contends that models are held over long periods of time and are relatively stable.

Mental models are of interest for two reasons. First, they influence cognitive functioning and second, mental models can provide science education researchers and teachers with valuable information about the learners' conceptual framework, that is, their underlying knowledge structures (Vosniadou, 1994).

Learners' Use of Mental Models

There are many reports in the science education literature indicating that learners' use of mental models is limited (e.g., Fensham & Kass, 1988; Harrison & Treagust 1996; Raghavan & Glaser, 1995). In some studies confusion in the use of has been attributed to the mode of instruction. For example, Smit and Finegold (1995) found Southern African physical science teacher-trainees viewed models as scale models of reality as a result of their exposure to medical models such as models of the human body, insects, skeletons and so forth. Similarly, Barnea, Dori, and Finegold (1995) report that Israeli pre- and in-service chemistry teachers failed to distinguish between a mental image and concrete model, and failed to realize that models also could be used for other purposes such as prediction.

It seems that learners, unlike experts, fail to appreciate that the principal function of mental models in science is to aid in the understanding of some phenomenon; studies by Grosslight, Unger, Jay, and Smith (1991), Abell and Roth (1992) in the biological sciences, Bent (1984) in chemistry, and Raghavan and Glaser (1995) in physics support

this conclusion. Mismatch between scientists' and learners' perceptions may be due to the inability of novices to operate at the formal level. Gabel, Briner and Haines (1992) assert that chemistry can be described on three distinct levels, sensory, atomic/molecular, and symbolic. Commonly, a chemical substance is represented on the atomic/molecular level using models such as three-dimensional representations. However, many learners address chemical problems on one level alone, for example, using a purely symbolic approach. Consequently, some authors argue that it is essential for instructors to design problem-solving exercises that utilize all three levels in an integrated manner to foster genuine understanding, as opposed to merely achieving competence in the use of algorithms (Gabel et al., 1992; Nakhleh, Lowery, & Mitchell, 1996; Pestel, 1993).

There have been few studies of learners' mental models of metallic bonding, and those studies reported are confined to secondary school learners. It seems learners have a poor understanding of the bonding in metals, seeing metallic bonding as unimportant or in someway inferior to other forms of bonding (De Posada, 1997). Learners are able to use simple models like the common sea of electrons model to explain the properties of metals (Taber, 1995, 1998), but are unable to effectively use more complex models such as the electron drift model (Stephens, McRobbie, & Lucas, 1999). The relative paucity of studies into learners' mental models for chemical bonding stimulated us to conduct an investigation into learners' mental models for metallic bonding. In particular, we were interested to develop a better understanding of senior students, including postgraduates, understanding of this subject. The research goal for this inquiry was, to investigate if there are preferred mental models for the concept of metallic bonding for secondary, undergraduate, and postgraduate chemistry learners.

METHODOLOGY

Theoretical Framework

This inquiry has been conducted within a constructivist paradigm. We believe inquiries into science education such as that described in this work are best addressed using a hermeneutical and dialectical methodology in which individual constructions are elicited by interactive dialogue between the researchers and the participants. Inherent in this view is the stance that interactive dialogue must be conducted on neutral ground in order to reduce the influence of investigator bias (Johnson & Gott, 1996). Specifically, the authors subscribe to a social and contextual constructivist belief system and acknowledge that an individual's constructs are influenced by his or her environment and are subject to influence by prior knowledge, peers, learning experiences and other social interactions (Good, Wandersee, & St Julein, 1993; Monk, 1995; Tobin & Tippins, 1993).

The theoretical framework for this inquiry is based on Norman's (1983) typology of mental models; that is, models have been classified as the *target system*, the *conceptual model of the target system*, the *user's mental model of the target system* and the *scientists' conceptualization of the target system*. There are disparate views about the typologies for chemical bonding and modern bonding theory often does not recognize metallic bonding as a separate class (Metallic bonding, 1994). Nonetheless it is common in many teaching institutions, including those involved in this inquiry, to treat metallic bonding as a separate class of bonding. Examination of curriculum material and interviews with instructors from the institutions involved in this inquiry resulted in the identification of two *target models*; the *sea of electrons model* and the *band theory*, the latter being derived from molecular orbital theory.

Subjects and Context of the Inquiry

The sample chosen for the inquiry comprised a total of 24 learners with a spread of academic abilities, with eight chosen from each of secondary, undergraduate and postgraduate educational levels. The secondary school learners (aged 17-18) formed two cohorts—four females and four males from single-sex schools in a middle-class suburb of a New Zealand City. The male secondary school learners were, in general, less confident and outspoken than their female counterparts, although all students spoke freely during interviews. Participants were interested to pursue science-based careers and stated that they enjoyed chemistry. The undergraduate participants were intending BSc chemistry majors from a New Zealand University. Because the interviews for undergraduates were conducted late in the year after the completion of lectures, undergraduate learners had, at a minimum, completed two years of tertiary chemistry instruction. There were two male and two female 19-year old second-year undergraduate participants and two male and two female third-year undergraduate participants in the inquiry; the latter 21 year-olds of average academic ability. The postgraduate learners, four PhD candidates (two male and two female) and four MSc level candidates (two male and two female), were high academic achievers—a reflection of the entry requirements for postgraduate studies. In spite of this, there was a considerable spread in academic ability within this cohort, with some learners possessing outstanding academic records. All MSc candidates were purposefully chosen from the second-year class. The intention was to distinguish these postgraduates from final-year BSc learners: these selection criteria ensured that the learners had completed all of their pre-requisite MSc courses.

Data Collection

Data collection comprised two distinct stages. The first stage consisted of a detailed examination of curriculum material; lesson plans, lecture notes, textbooks, and workbooks used by learners, combined with informal interviews with the instructors involved in the inquiry. The synthesis of these data comprises the scientists' conceptualization of the target systems of the inquiry (Norman, 1983). From these descriptions, criterial attributes were developed for each target model. Criterial attributes, negotiated with six independent experts—two high school teachers and four tertiary level instructors, represent the essential qualities, all of which must be recognized if the model is used in a way that is acceptable to scientists. The criterial attributes for a given target model may vary depending on the level of the learner, as negotiated with experts. The second stage of data collection involved elicitation of learners' (i.e., users', according to Norman's terminology) mental models of the target systems, obtained by means of semi-structured interviews, including the use of an IAE approach. Learners' preferred mental models for metallic bonding were probed using the following interview protocol for which elicitation of learners' views comprised five tasks (Table 1).

Insert Table 1 about here

Insert Figure 1 about here

Development of IAE focus cards was based on an eight-step algorithm prescribed by Gilbert, Watts, and Osborne (1985). Learners were encouraged to draw their models; however, some respondents preferred to describe the bonding verbally and were not

pressurized. At the beginning of the interview, most learners indicated a preference for a given model and the interviewer probed his or her familiarity with that model. If a learner did not identify a preferred model, the interviewer simply probed his or her understanding of metallic bonding.

Data Analysis

All interviews were audiotaped and fully transcribed. Participant-validated transcripts were inspected for statements that revealed learners' views for metallic bonding. These statements were compiled to form an inventory for a given target model and these data were combined with learners' drawings to develop a view of their mental models. Portions of transcripts support the summary of the research findings reported here; pseudonyms have been employed to protect participants' confidentiality. Transcripts have undergone light editing (removal of repeated words, changes of tense, etc.) to improve readability. The six independent experts also validated the summary of the research findings.

Task 1 of the interview protocol, in which learners were shown a sample of aluminum foil, was the main probe used to elicit learners' *preferred* mental models for metallic bonding (Table 1). Further data on preferences were provided by task 5 (Table 1), involving elicitation of learners' choices of the depictions provided in Figure 1. Reflection on the results of a trial study indicated that this protocol in which learners' views were elicited in a more open-ended fashion (i.e., using aluminum foil as a prompt) before any target models were introduced (i.e., using Figure 1) appeared to be less likely to influence learners' responses.

Learners' understanding of their mental models was probed by reference to the criterial attributes for the sea of electrons model, the sole model of choice. There were four criterial attributes identified for the sea of electrons model; *lattice structure*, *electron mobility*, *interstitial alloys*, and *substitutional alloys*. The interviewer monitored learners' descriptions of their mental model as the interview progressed. In many instances, learners made specific reference to criterial attributes spontaneously; if they did not, the interviewer probed their views with prompt questions. For the criterial attributes of lattice structure and electron mobility, most learners offered spontaneous responses. For the remaining criterial attributes, that is, alloy formation and structure, the use of a sample of steel wool (task 2 in the interview protocol, Table 1), enabled the interviewer to probe participants' understanding.

Learners' *use* of their mental models was probed by task 3 and 4 (Table 1) that is, the use of the IAE cards depicting model use. Two events of model use were chosen, one that depicted the difference in conductivity between a copper wire and a non-conductor (a glass rod), and a second that illustrated the malleability of metallic copper.

The research findings from this inquiry are summarized under three headings, learners preferred mental models for metallic bonding, learners' understanding of mental models for metallic bonding, and learners use of mental models for metallic bonding.

LEARNERS' PREFERRED MENTAL MODELS FOR METALLIC BONDING

Learners' preferred mental models for metallic bonding varied depending on their academic level; the research findings are described for each level of learner in turn, concluding with a summary.

Secondary school learners

When describing the bonding in aluminum foil, five participants stated that their preferred mental model for metallic bonding was the sea of electrons, identifying the key feature of the model, namely, mobile, delocalised electrons. For example, Frances stated, "a sea of electrons is when the electrons are all delocalised, you can't really see where the electrons are". However, despite specifying the sea of electrons as their preferred model, some learners' descriptions were inconsistent with curriculum material. David, for example, drew Figure 2 and stated, "the metal is in a sea of electrons" but went on to state "the mental image I would have would be a sandwich type of thing" and that "I don't know if there are any [electrons] between the atoms".

Insert Figure 2 about here

Of the remaining learners, Anne and Anita did not appear to possess any coherent mental model for metallic bonding, their explanations consisting of macroscopic physical properties of metals rather than a description of metallic bonding. This aspect is illustrated by Anne's description of the bonding in aluminium foil that "it's held together quite strongly" but when asked if she had a model in mind of the way it would be held together she replied "not really". In contrast, when describing his mental model for the

bonding in aluminium foil, Keith appeared to utilize the octet rule invoking the formation of covalent bonds. Having drawn two aluminium atoms (Figure 3) and describing the dots and crosses as electrons, he went on to state "the aluminium ion there needs three more electrons to satisfy its full outer shell so it's bonding with that which has got three full ones".

Insert Figure 3 about here

Secondary school learners' choices of depicted models for lithium (Figure 1) were consistent with their mental models for the aluminium foil, with six learners choosing depiction B, a simple depiction of the sea of electrons model. It is interesting to note that learners like Anita who held no clear mental model for metallic bonding chose depiction B, whereas other learners like David who specified the sea of electrons model when describing the bonding in aluminium foil, did not choose B. Reasons for choice B were its familiarity and depiction of free electrons as was summarized by Anita who stated, "that's how we normally see it textbooks, and the others look totally confusing". Two learners preferred choice D, with five learners in total indicating that D held some appeal. Choice D, was selected by Claire "because you can see that the electrons are all moving around, and they are not attached, and you have got the nuclei there. D is a good 3-D representation of how I sort of think the nuclei [sic] are arranged"

Learners' responses when probed as to the depiction that held least appeal were briefer. Depiction C was, perhaps not surprisingly, the least appealing, typically because it was unfamiliar or considered unclear, as stated by Richard—"I don't know what's going

on there. It's just not clear", and David, "it doesn't have any resemblance to what I think an atom would be".

Undergraduate learners

Undergraduate learners shared similar views to their secondary school counterparts, with four learners specifying the sea of electrons model for metallic bonding. In contrast to the secondary school learners, undergraduates who chose the sea of electrons model, provided more comprehensive explanations as illustrated by Steve's response and drawing (Figure 4).

> So you have got a system, this is a row of monovalent cations in a delocalised sea of electrons around it, and that's the metal bonding [drawing lines linking negative charges with Al+].

Insert Figure 4 about here

Steve has indicated that he believed aluminium contains monovalent cations in contrast to the scientific conceptualisation which would assume loss of all the valence electrons and production of tervalent cations. In addition, in his drawing of his model shown in Figure 4, Steve appears to indicate that there are bonds between electrons and aluminium atoms. However, upon probing he was able to explain the origins of the attractive forces within the metallic substance in a manner consistent with the scientific view stating, "it's the electrostatic forces of attraction between aluminium cations and the electrons". The

remaining undergraduates held a variety of mental models for metallic bonding. Three learners had no clear picture of the bonding in metals, as typified by Bob's response in which he stated "I honestly don't have much idea except that in some way I see the metal as being close together in some regular fashion".

Undergraduate learners' choice of depicted models from Figure 1 was different to that of secondary school learners with five learners choosing depiction D, three B, and one A. Reasons for choices, likewise to secondary school learners, were the aesthetically appealing three-dimensional nature of D, with, for example, Phill stating "you can see it all quite simply" and Bob stating that he liked the "regular arrangement" of lithium atoms, and the simplicity and familiarity of B. Depiction A was most disliked by five learners, because they saw it as inferring a molecular, rather than continuous structure; Bob stated that "it shows Li_2 molecules which has been told to us many times doesn't exist" and Alan said that "it is showing lithium-lithium type bonds and it's arranged as a diatomic structure". Two learners disliked choice C, and again, the reason given was its complexity as illustrated by Mary's comment that "I don't really understand B".

Hence, overall undergraduates, like secondary school learners, preferred the sea of electrons model but differed in their choice of depicted models.

Postgraduate Learners

The preferred mental model for postgraduates also was the sea of electrons model. Interestingly, whilst postgraduates in general provided more complete descriptions of their mental models than did their secondary school counterparts, two struggled. Grace appeared to possess no model for metallic bonding stating "I don't know" and Christine

stating "I don't actually think of them as being bonded". Notwithstanding the above comments, postgraduates' descriptions of their preferred model more commonly incorporated concepts such as electron cloud, molecular orbital, from other target models, as illustrated in Kevin's response "what makes it metallic bonding is the fact that you have this electron cloud. The electrons are not associated with specific atoms as such they are shared around".

Postgraduate learners' choice of depicted models was similar to undergraduate learners. Six learners preferred choice D, one choice B and the other choice C. The justification for choice D was that the depiction was more useful in showing the arrangement of atoms in aluminium, for which Kevin stated "you have got the lattice sort of arrangement which is what I automatically think of when I think of a metal". Although most learners chose D, the postgraduates were much more ambivalent about their choice, often changing their minds, typically evaluating the strengths and weaknesses of all choices extensively before settling on a final choice. Christine's response exemplifies this aspect of model selection for postgraduates.

> *Christine*. I don't like A. I probably don't think of it as being like B either. Aesthetically I like D but I think it is C, I don't think of bonding because I know about orbitals and stuff like that. I don't know if it is just its familiarity.
>
> *Interviewer*. That's in relation to C? Is that what you mean?
>
> *Christine*. Yeah. Like I wouldn't pick those two [indicating A and B, Figure 1].
>
> *Interviewer*. So you wouldn't pick A or B. Which one appeals to you most? It is D, is that right?

Christine. If I were looking at them straight, I'd say D and C. I see discrete atoms. I'd probably think of them single atoms, and that shows how they are packing. But C would be the actual bonding interaction in it.

Interviewer. Can you just tell me why you like D then? Start with D. D if I understand what you said, you like D because it appeals to you, and you said that's how you see them packing is that right?

Christine. Yeah.

Interviewer. OK. So C, can you tell me what appeals to you about C?

Christine. Because it's to do with energy. Like you can see that, for instance, you've got your orbital for one lithium atom and you could have another one over this side [indicating RHS part of C in Figure 1], and then you would combine to bring the energy down so that you would actually get an orbital where the electrons would go in.

Depictions A and C were least chosen for similar reasons as the secondary school and undergraduate learners, namely, the inference of molecularity in A and the complexity of C. It was, however, notable that dislikes, as for preferences, were more mixed, typified by Jenny's response that "part A has two lithium atoms joined by a single bond, it doesn't appeal to me at all". Rather than merely expressing preferences, postgraduate learners evaluated the depictions of bonding, indicating what they perceived to be limitations or alternative conceptions.

Summary

Secondary school learners' preferred mental model for the bonding in aluminium foil were consistent with their choices of depicted models namely, the sea of electrons

model. In contrast, undergraduates and postgraduates preferred a realist space filling depiction, provided more detailed explanations of mental models, and were more critical of depicted models.

LEARNERS' UNDERSTANDING OF MENTAL MODELS FOR METALLIC BONDING

Learners' understanding of their mental models for metallic bonding was evaluated against the criterial attributes for the model. As expected, learners' understanding varied depending on their academic level. The data are summarized according to academic level, concluding with a summary of the findings.

Learners' Views of Lattice Structure for Metals

In addition to the more detailed explanations regarding their preferred mental model described above, undergraduate and postgraduate learners evidenced greater understanding of the lattice structure and continuous nature of the bonding in metallic substances than did their secondary school counterparts. Unlike secondary school learners, postgraduates typically drew diagrams showing lattice structures with little or no prompting. In contrast, some secondary school learners when questioned about the structure of the metallic lattice confused this with the electronic structure of atomic aluminium, for example, to the question about what aluminium would be like on a very small scale, Anne's response was "what do you mean, like the nucleus and the shells?". It appeared that Anne misunderstood the question. However, an attempt at clarification was no more illuminating. Keith likewise seemed confused by the question, again thinking of

the electronic structure of the aluminium atom, rather than the lattice structure. Similarly, in response to the interviewer's question about what sort of mental picture she held for aluminium, Anita appeared to have no appreciation of the regularity of the metallic lattice, describing the lattice structure of aluminium as "a big mess". Some secondary school learners did show a limited appreciation of the structure and continuous nature of metallic lattices. Claire described metallic aluminium as containing "layers on top of the others, like graphite is sometimes drawn with the layers of carbon atoms".

The descriptions of metallic bonding provided by undergraduate learners were more characterized by the spontaneous introduction of domain-specific terminology used for the lattice structure such as close-packed, cubic close-packed, and hexagonal close-packed.

> *Bob*. I know they are arranged because we have been told that anyway. Like close-packed, cubic-close-packed those type, those types of things.
>
> *Interviewer*. OK so the atoms or nuclei you mentioned. Can you tell me how you see them organized in space?
>
> *Alan*. Like the close-packed arrangement?
>
> *Interviewer*. What does close-packing mean to you.
>
> *Alan*. There's cubic close-packing, hexagonal close-packed, of the spheres.

Some undergraduate learners provided highly detailed descriptions, including discussion of lattice holes, and a description of the build-up of layers that results in the close-packed

structures. Jane, who went into considerable detail describing the structure in terms of interstitial holes, provided the most comprehensive explanation.

> *Jane*. I think of them as being like atoms, and then they are hard to draw that way...mm, and then you have got like the lattices and stuff [draws cluster of circles, top of Figure 5], and you have got octahedral holes and tetrahedral holes.
>
> *Interviewer*. Just looking at those two diagrams you have drawn. On the left side you have got three rows and on the other side to that you have got something else, what's the difference between those two?
>
> *Jane*. That's kind of like I was trying to show, that's looking up from the top or something and you have got like the hole [draws arrow pointing to circles, top RHS Figure 5]. Then like you might have another layer underneath, but that's hard to see and then you find that in the hole you could have [draws four circles in diamond pattern and dotted circles over-lying this [lower, RHS of Figure 5] [respondent laughs].
>
> *Interviewer*. Those dotted ones you have drawn, that's the next layer underneath is it?
>
> *Jane*. Yeah, and then you can imagine the hole being in there.

Insert Figure 5 about here

Some undergraduates were rather vague in their descriptions of lattice structure. Kim for example, expressed a view of the structure similar to that of secondary school learners describing the arrangement as consisting of layers.

Similar to the undergraduates, postgraduates' explanations contained spontaneously introduced terminology, exemplified by Jason's explanation.

> A whole lot of metal atoms are basically all stacked as closely as possible together. There's a bunch of different metal structures like cubic and hexagonal close-packing and then the body-centered cubic, so basically all the metal atoms are as close together as they can possibly be.

Undergraduate and postgraduate learners' choice of models with structures that depicted three-dimensional lattices (Figure 1) is consistent with their spontaneous descriptions discussed here and supports the view that they possess a greater appreciation of the continuous nature of ionic lattices. However, the greater aesthetic appeal of the space-filling type depictions also may have been a factor in model choice.

Learners' Views of the Structure and Bonding in Alloys

Across all three levels of learners, it was stated that the bonding in steel wool was essentially the same as in the pure metallic substance aluminium. Secondary school learners mostly failed to recognize that steel was an alloy containing iron as a base metal, with a variety of other metals substituted into the lattice, and also containing interstitial carbon as a hardening agent. Claire stated, "it's metallic. I don't see how it is different", and Frances, "it would be the same bonding because they are both metals". Keith and David did identify steel as an alloy, and one form of alloy—a substitutional alloy, but failed to provide any detail with Keith simply stating "it'd have different kinds of atoms" and David that steel wool was "a mixture of metals".

More undergraduates than secondary school learners identified steel as an alloy but they also were vague about details. Reneé and Steve both showed an appreciation of the interstitial nature of the alloy steel, Reneé indicating that carbon is "in the middle" of the metallic lattice and Steve stating, "I would expect you would get a certain amount of carbon in there as well". Alan showed an appreciation of the nature of alloys describing steel as a mixture of metals, however, in his subsequent description he confused substitutional alloys with interstitial alloys, failing to appreciate that interstitial atoms are more commonly non-metals like carbon.

> *Alan.* It'd be made up of two separate metals, that's in the steel.
>
> *Interviewer.* How would you see the atoms of those different metals organised?
>
> *Alan.* Oh, um, alternating…matrix I guess you could say, of the different metals. You'd probably have the larger atoms surrounded by the smaller ones in a...it'd depend on the ratio of the smaller atoms.
>
> *Interviewer.* Can you just tell me a bit more about that?
>
> *Alan.* Yeah. If you have the big one [draws two large circles and a series of smaller circles surrounding them, Figure 6] but the smaller one's surrounding it and then the next one, and so on.

Insert Figure 6 about here

Postgraduate learners routinely identified steel as an alloy but learners who did not possess clear mental models for metallic bonding, such as Christine, Grace and Rose, were unable to provide much detail about the bonding in the alloy steel. Christine, for

example, struggled to explain the bonding in steel in a similar way to that for aluminium, but she did recognize that it was a mixture of metals. Brian identified the sea of electrons model in his description of the bonding in aluminium, but for steel wool failed to identify steel as an alloy stating, "the bonding would be identical, they are different metals, and their overall bulk properties would be different. But apart from that, I don't really see any major difference".

Jason provided by far the most comprehensive picture of the bonding and structure for steel wool, although he neglected to mention substitutional metal atoms.

> *Jason.* How I would see the bonding, the bonding would be fairly similar to the previous sample [i.e., aluminium foil]. The only difference is that this is actually steel, and the only difference is that it has got some interstitial carbon in it.
>
> *Interviewer.* OK. Could you just tell me what you mean by interstitial carbon?
>
> *Jason.* Well when you pack the iron spheres together there's still space, they're not cubes, so they can't pack completely so there's no space at all.
>
> *Interviewer.* So they are not cubes?
>
> *Jason.* The atoms? No. I am sort of regarding them as spheres. So there's space and if you do the sort of geometric modeling, there's about twenty-four percent or so I think.
>
> *Interviewer.* Twenty-four percent?
>
> *Jason.* Space. So the rest of this can be filled up by other smaller atoms and steel is, um, carbon and iron all mixed together in a certain percentage. Those carbon atoms are incorporated in the lattice, so the carbon atoms almost take on a, they help to lock the structure in place and that's why steel is harder than iron.

Again like learners' mental models of metallic bonding, it seems that undergraduate and postgraduates show increasing sophistication in their explanations of criterial attributes compared with their secondary school counterparts, albeit possessing a similarity in preference for simple models like the sea of electrons.

Summary

Undergraduate and postgraduate learners possessed a greater understanding of the lattice structure and continuous nature of metals than did secondary school learners and introduced domain-specific terminology to aid their descriptions. However, no learners evidenced a complete understanding of the bonding and structure of alloys.

LEARNERS' USE OF MENTAL MODELS FOR METALLIC BONDING

There was considerable variation in learners' ability to use their mental models to explain the conductivity and malleability of metallic substances. Learner's use of their mental models is summarized according to their academic level, concluding with a summary of the findings.

Learners' Explanations for the Conductivity of Copper Wire

Secondary school learners typically used concepts from the sea of electrons model to explain the conductivity of copper, namely, free or mobile, electrons, whereas the non-conduction of glass was typically attributed to fixed electrons. Claire, for example, stated, the copper rod "is metallically bonded, it's got lots more electrons going around the nuclei. So the electrons are free to move and carry the current that makes the circuit

complete". Here, Claire, although consistent with her description of the bonding in aluminium foil, inappropriately associated metallic bonding with "more electrons". Neil believed "there's no free electrons in the glass rod and there is in the copper wire" whereas Richard stated, "the electrons are free to move" because in its bonding "the copper has a sea of electrons". Two secondary school learners, Anne and Anita, introduced other ideas to explain the conductivity of copper wire, in Anne's case she referred to ions, "copper's got ions that can allow a flow of electrons" and Anita referred to the spacing of atoms in the metallic lattice "in the glass rod the bonds are not close enough, whereas in the copper wire they are really close together, close enough to let the electrons go through".

It might seem reasonable to expect learners who chose the sea of electrons model as their preferred model for metallic bonding would then use this model to explain the physical properties of metals. However, for undergraduates there was no obvious correlation between model choice and model use. Undergraduates did refer to mobile and free electrons, but often introduced ideas from other models such as the molecular orbital theory. In instances for which there was no clear model choice in the first place, learners borrowed terms and concepts from other models. Bob, for example, appeared to possess no clear mental model for metallic bonding. He began his explanation of the conductivity of copper wire with the introduction of the molecular orbital theory and introduced the idea of delocalised electrons. However, he did not relate the concept of delocalisation to bands consistent with the molecular orbital-based band theory, rather his explanation is more consistent with the sea of electrons model.

> It'd be to do with the electrons in molecular orbitals holding, well it wouldn't be a molecule, because it's not really a molecule obviously. But the electron doesn't seem to have any particular, or the electrons don't seem to have any particular individual nucleuses. It sort of moves over them. So you have, if you had a potential across, it'll migrate across. As some come in one end, they'll be pushed off the other, and the glass rod not being crystalline for a start, is more metallic um...um.. you know amorphous type thing I guess. There's no electrons, it's covalent bonding rather than metallic bonding.

Undergraduates who specified the sea of electrons model explicitly, offered more coherent explanations as illustrated by Steve's explanation and drawing (Figure 7).

> *Steve*. OK with the glass rod you have got, it is basically a silica structure inside the glass, and that is silicon covalently bonded in a sort of silica structure with sort of units like [drawing SiO_4 unit, LHS Figure 7]. Whereas in the copper wire, you have got the metal bonding that we talked of before, with a delocalised sea of electrons [draws two Cu^+ with negative signs around them, RHS Figure 7] and so when you apply a potential to the copper wire, it enables the electrons to flow freely in the delocalised sea from one side to another [draws arrow] setting up a current and that's why you get your light glowing. But because you have got covalent bonding, and electron sharing rather than the electrostatic sort of bonding that you have got with the metal bonding, it's not possible for the electrons to move through the system freely [draws arrow under SiO_4 unit].
>
> *Interviewer*. Why is that not possible in that case?

Steve. Because the electrons are tied into this covalent bond here [draws line enclosing one Si—O bond], where they are shared between the silicon and the oxygen rather than being in a sea of delocalised electrons.

Insert Figure 7 about here

Postgraduates, related conductivity to the mobility of electrons with James stating "it's the delocalised electrons that are able to flow around over the positive centers", Christine "the copper has the electrons that can move around" and Brian "the copper wire is a conductor because of the delocalised electrons, they are not restricted to bonds, the electrons can move". It is interesting to note that Christine used the notion of mobile electrons here to explain the conductivity of metals although, as reported earlier, she appeared to possess no clear mental model for metallic bonding. Despite the sea of electrons model being a common choice for postgraduates, in a similar way to the undergraduate learners, there was not necessarily a correlation between postgraduates' choice of model and how they explained the conductivity of copper wire. For example, Jason's preferred model for metallic bonding was the sea of electrons model, however, his explanation of the conductivity of copper wire was inconsistent with his model choice, perhaps as a result of his focus on the nature of the bonding in the glass rod.

Jason. OK well the glass rod is, well an insulator it's very difficult for electrons to pass through the glass. As far as the copper wire is concerned [drawing Figure 8], you've got a very, very narrow piece of copper wire so it'll see the electrons which are getting pushed along if you like by the battery or dragged along.

Interviewer. The spheres are the atoms are they?

Jason. Yep they're not very well packed. OK and so an electron, for example, experiences a general force in that direction [drawing arrow] and so it sort of transverses along through, and eventually you get a net flow of electrons in one way or the other.

Insert Figure 8 about here

In Jason's explanation, there is no attempt to relate the conductivity directly to the presence of free or mobile electrons that form a crucial part of the sea of electrons models, although his explanation infers that the electrons able free to move through the copper wire.

Learners' Explanations for the Malleability of Copper

Learners' use of their mental models for metallic bonding also was probed by asking them to explain the malleability of copper metal, illustrated in an IAE focus card, which for all learners proved more problematic than the conductivity of copper wire. Secondary school learners used a number of terms such as squished, squashed and flattened to describe the event. Others were even more vague, Anita, for example, stated that the copper atoms move because they have been placed "under pressure" and so have "gotta go" when subjected to pressure. For some learners, the malleability of copper was explained in terms of changes to the size and/or shape of atomic species, be they ions or atoms, and rearrangement of lattices as illustrated by Neil who claimed that the copper atoms "would be sort of reshaped". Others were familiar with the term malleability,

indicating that they had encountered it during instruction, but likewise were unable to clearly explain the event depicted on the focus card. Frances, for example, recognised that metals are malleable and change shape, stating that "the whole atom structure will be moved around", but went on to state that the spheres in the thick block would be "more spaced out", whereas those in the thin sheet would be "more compact"

Undergraduates offered more detailed explanations for the malleability of copper than did secondary school learners and commonly related their explanations to their mental model for metallic bonding. Some, like Bob, struggled to explain the event but, like his explanation of conductivity of copper wire, he attempted to explain this event using molecular orbital theory, stating "if the electrons were in a molecular type orbital, although there are no molecules in it, it's a metal, they would have a slight tendency to be slightly pliable sort of move around each other". Steve used his mental model of sea of electrons to explain the event, and was the only learner able to relate his explanation clearly to the bonding in the metallic substance.

> OK, well you have got the copper metal bonding in the same sort of system as I had before [draws row of Cu" with negative signs inside circles between rows, Figure 9], with the delocalised electrons, where you have a sea of delocalised electrons that are relatively free to move throughout the whole structure. Then the structure is relatively free to sort of move whenever a pressure is applied to it. It's easy for it to sort of be pressed down as it were, to change it's shape, so there is a freedom of compression so these can come in closer to each other [draws arrows towards the centre of rows], and therefore it presses the rod down into a sheet which would be denser.

Insert Figure 9 about here

Interestingly, here Steve made the assumption that the density of the copper has changed. However, he altered this stance when probed further "actually no, come to think of [it is not more dense]. Because the sheet whilst being thinner, is also a lot wider". Whilst Steve offered probably the most convincing explanation of all learners in this inquiry it is still incomplete. For example, neither Steve nor any other learners seemed to be able to reconcile the strength of metallic bonding with the malleability of metallic copper. The remaining undergraduate learners offered simple explanations, like the secondary school learners, describing the rearrangement and movement of atomic species typically relating this to a perceived lack of strength of metallic bonding as seen in Jane's response.

> It's just rearranged. They have still got the same kind of bonding there. It's not bonding, the same kind of packing and it'd just change the shape of the whole thing. It's still, there's still on the atomic scale the same, the same pattern. Like you have only changed the real massive kind of shape.

Postgraduates also offered rather incomplete explanations for the event. Some like Rose had no idea at all, only describing the physical changes associated with the event stating, "I guess it must be more spread out". Terms like squishing and flattening were again common, although it seemed that postgraduates do not harbor the alternative conception that atom volume or spacing between atoms is reduced as exemplified by the views of James "the atoms can move across each other they are not held by distinct bonds holding them in place" and Christine "when it's coming through the other end its like you

are squishing the layers and so you still have the copper interaction but they are more two dimensional". Interestingly, Jason failed to use his mental model of sea of electrons to explain the malleability of copper, although his explanation was highly detailed.

> *Jason*. I don't have a good understanding of actually how the bonding between these atoms works [drawing array of circles close together; top part of Figure 10]. But because the forces are not particularly directional, each one has sort of twelve nearest neighbors; they can be pushed past one another with reasonable ease.
>
> *Interviewer*. So what happens when they are pushed past each other?
>
> *Jason*. Well I guess I basically see this [draws four more circles close together; middle part of Figure 10] go through a process where they start in this kind of configuration here, which is hexagonal-close packed [writes *hcp* next to middle circles]. OK, and then it experiences a stress in one direction or another. It slips [draws arrow above middle circles] into this kind of configuration [drawing four spheres in square arrangement; lower LHS of Figure 10, writes *bcc*] in which it has less nearest neighbors. I've just drawn it in two dimensions here to make it simple. Like this one would have six nearest neighbors [indicating the *hcp* structure] and this one would just have four [indicating *bcc*]. So because the directionality isn't too strong, it can endure going from six nearest neighbors, to four, and so that's *bcc*. Then as it experiences more stress, it sort of flops back over into the other one here [draws four circles in diamond shape; lower RHS of Figure 10, writes *ccp*].

Insert Figure 10 about here

Summary

Learners were able to use their mental models to provide reasonable explanations for the conductivity of metallic copper, but struggled to offer explanations for its malleability. There was no consistent correlation between the choice of mental model and the model used to explain physical properties of metals and undergraduates and postgraduate introduced concepts from other bonding models to aid their explanations.

CONCLUSIONS AND IMPLICATIONS FOR TEACHING AND LEARNING

There was clear choice for the sea of electrons model across all academic levels of learners who seemed to see free or mobile electrons as a key feature of the bonding in metals. Undergraduate's and postgraduate's possessed a greater appreciation of the continuous nature of the metallic lattice, and their descriptions included the use of domain-specific terminology to describe lattice structure. This preference also was reflected in choice of depicted models, with undergraduates and postgraduates choosing structures that depicted the three-dimensional lattice in more detail. In addition, these learners utilized concepts from other models to aid their explanations and descriptions of their mental models. As would be expected, undergraduate and postgraduates explanations were more detailed and complete, and these learners were far more analytical and critical of depicted models for metallic bonding. Despite this latter observation, few learners at any level appeared to possess a complete scientifically acceptable mental model for metallic bonding as evaluated against criterial attributes.

The data regarding learners' mental models for metallic bonding suggest that learners from all three academic levels prefer simple or realist mental models of the target system of metallic bonding. Although advanced learners commonly held a number of mental models, they did not link models in any convincing fashion. Frederiksen, White and Gutwill (1999) suggest that it is important that students are able to construct derivational linkages among models and it would appear that the instruction experienced by the learners in this inquiry has not resulted in the formation of clear links. The extra depth of explanation for the models of bonding by undergraduates and postgraduates compared with secondary school learners is likely a reflection of their learning experiences. Examination of curriculum material revealed that undergraduates and postgraduates have been exposed to a greater range of instruction for the topic than have secondary school learners. The findings of this inquiry are consistent with that those of other studies involving abstract chemistry concepts like atomic structure. For example, previous studies found that secondary school learners prefer realist space-filling models of atoms and molecular species (e.g., Harrison & Treagust, 1996; Pereira & Pestana, 1991; Taber, 1998). The extra depth of explanations of mental models provided by more advanced learners in the present work is consistent with the findings of Kleinman, Griffin and Kerner (1987) and suggests that older learners are capable of an increased level of abstraction and possess a greater number of mental images. Since there is considerable commonality across all three levels of learners, this suggests that learners retain mental models for considerable lengths of time. Hence, it appears that the mental models preferred by the learners in this inquiry are stable in contrast with the assertion of Johnson-Laird (1983), but consistent with the view of Norman (1983). Nonetheless, the

data revealed that learners' mental models are frequently incomplete as asserted by both Norman and Johnson-Laird. Furthermore, there was evidence that learners' ability to operate or use their mental models, for example, to explain events involving model use depicted on IAE focus cards, was limited.

It is important to note that the first part of the present work was concerned with learners' *preferred* mental models. Hence, the finding that even able and senior learners prefer simple models does not necessarily mean that they have limited understanding of more sophisticated models; indeed the high level of their academic achievements revealed in their academic transcripts indicates otherwise. What the inquiry suggests is that despite competence in the description and use of sophisticated mental models for chemical bonding, learners prefer simple models and relate to more abstract models in the context of tests or examinations. Consequently, the observation that learners prefer simple models, whilst likely not the intention of their instructors, and being somewhat surprising in the case of the advanced level learners, is not necessarily cause for concern. However, these findings raise the question as to the advisability of teaching sophisticated abstract mental models for the concept of chemical bonding. Indeed, some authors suggest that teaching of highly abstract models at the introductory level is counter-productive. For example, Gillespie, Spencer, and Moog (1996a, 1996b) suggest that there is little point in teaching molecular orbital theory to undergraduates. Ogilvie (1990) and others (e.g., Bent, 1984a; Tsaparlis, 1997; Weinhold, 1999) support a view that "the quantitative and mathematical quantum-mechanical theory applied to molecular structure and properties is unnecessary and irrelevant in the general chemistry and undergraduate curriculum" (Ogilvie, 1990, p. 288).

Instructors use and build upon sophisticated abstract mental models, such as those for metallic bonding described in this inquiry, in order to develop other concepts such as spectroscopy and the development of reaction mechanisms or reaction schemes. Moreover, the high academic achievement of the tertiary level learners involved in this inquiry suggests that they are able to use these models for such purposes. Consequently, it is not feasible to remove them from the curriculum. However, it may be advisable to limit the teaching of such models until the advanced levels of the undergraduate degree since chemistry non-majors will have little need for models in their subsequent studies.

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Table 1

Interview Protocol for the Five Tasks Used in the Inquiry

Task 1. Shown a sample of aluminium foil—*please describe the bonding in this substance*
Task 2. Shown a sample of steel wool—*please describe the bonding in this substance*
Task 3. Shown an IAE focus card depicting conductivity of copper wire compared with that of a glass rod—*please explain this process*
Task 4. Shown an IAE focus card depicting the malleability of metallic copper—*please explain this process*
Task 5. Shown a focus card containing depictions of metallic bonding taken from curriculum material (Figure 1)—*which of these models appeals most/least to you?*

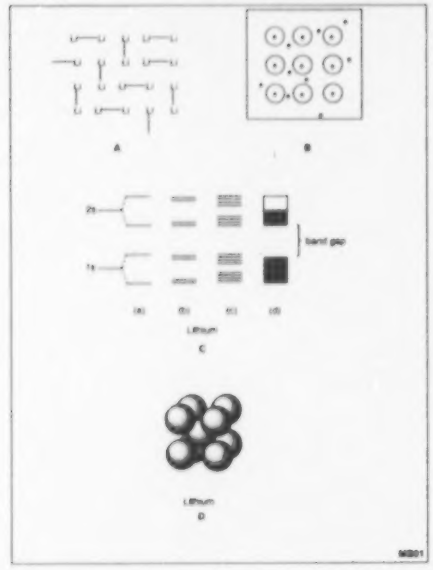

Figure 1

Focus card of depicted models for metallic bonding used in the inquiry

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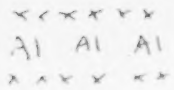

Figure 2

David's drawing illustrating the bonding in aluminium foil

44

Figure 3

Keith's drawing illustrating the bonding in aluminium foil

45

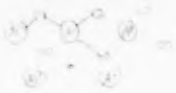

Figure 4

Steve's drawing illustrating the bonding in aluminium foil

Figure 5

Jane's drawing illustrating the structure of the aluminium lattice

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Figure 6

Alan's drawing illustrating the structure and bonding in steel wool

Figure 7

Steve's drawing illustrating the conductivity of copper metal and non-conductivity of glass

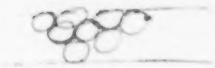

Figure 8

Jason's drawing illustrating the conductivity of copper metal

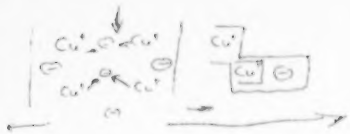

Figure 9

Steve's drawing illustrating malleability of copper metal

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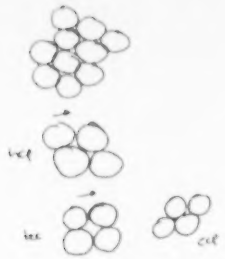

Figure 10

Jason's drawing illustrating of the malleability of copper metal